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Dynamic Thermoelectric Modelling of Oil-filled Power Transformers for Optimization of Offshore Windfarm Export Systems

Syed Hamza Hasan KAZMI *
Ørsted Offshore Wind
Denmark

Joachim HOLBØLL
Technical University of
Denmark

Thomas Herskind OLESEN
Ørsted Offshore Wind
Denmark

Troels Stybe SØRENSEN
Ørsted Offshore Wind
Denmark

SUMMARY

Oil-filled power transformers are some of the most critical components of the electrical export system for Offshore Wind Power Plants (OWPPs). During contingency situations, dynamic loading of the export transformers becomes essential for debottlenecking and optimization of OWPPs, which is elaborated using a case study of Anholt offshore windfarm export system power transformers. Power transformers can be dynamically loaded if the temporal development of temperatures is known, especially Top-Oil (TOT) and Hot-Spot (HST) temperatures. Since the fibre-optic sensors for direct HST measurements are unavailable and the associated costs are high, these temperatures must be estimated using thermoelectric models based on differential-equations for real-time dynamic loading operation of transformers.

The renowned and industry-wide accepted thermal model of IEEE loading guide C57.91 is presented in this paper, along with the recently established but well proven model by Susa *et al.* Both these models are validated using the instantaneous TOT measurements for one of the 140 MVA, 225kV/33 kV transformers in the Danish Anholt windfarm for the entire 2017 period. The model that is found to perform better is then used for HST calculation for the transformer and the thermal aging of its paper insulation is assessed based on its loading and ambient conditions history for 2017.

Furthermore, the thermal utilization and insulation loss-of-life (*LOL*) based on HST variation of the Anholt windfarm transformer is assessed for increased wind energy generation for 1 year. This is done by upscaling the actual instantaneous load of the test transformer for the entire period of 2017. The upscaling factor '*W*' is varied over the range of 1.0 to 1.6 pu with the actual instantaneous wind generation in 2017 at Anholt as base. The results are then used to provide insights into transformer dimensioning for offshore windfarm applications and to assess whether the transformer allows further wind energy integration in the existing export system for the Anholt offshore windfarm.

KEYWORDS

Power Transformers - Thermoelectric Modeling - Offshore Windfarms - Transformer Thermal Utilization - Hot Spot Temperature - Transformer Loss of Life - Thermal Aging.

* syeka@orsted.dk

1. INTRODUCTION

Offshore Wind Power Plants (OWPPs) contributed a sizeable portion of the annual wind energy generation in Denmark in 2017 [1], which is projected to increase even further over the next two decades. Similar trend is observed in the energy outlook of global leaders (including UK, USA, Germany etc.). However, the bottlenecks in OWPP export systems and the grid upgrade costs associated with the available solutions for these constraints are potential barriers to this projection [2]. Oil-filled power transformers are core components of the OWPP export systems and can result in system bottlenecks.

Direct Hot-Spot Temperature (HST) measurement of transformer winding using fibre-optic sensors has been investigated continually in recent times, but application of these methods for wide-scale thermal assessment of power transformers will only be possible in the distant future [3]. Therefore, estimation of transformer's extremely important operational parameters Top-Oil (TOT) and Hot-Spot (HST) temperatures under varying load and ambient conditions can either be performed using accurate but complex-to-design Computational Fluid Dynamics and Thermal Hydraulic Network based models [4], or by differential equations-based thermoelectric models [5] [6] [7] [8], which are simpler to design and offer sufficient accuracy. Moreover, these models can adequately perform real-time thermal evaluation, making them suitable for wide-scale dynamic loading applications [9].

In this paper one of the Anholt offshore windfarm export transformers is used as the test case. Instantaneous TOT measurements of the transformer for the entire 2017 are used for validation of the selected thermo-electric models. The actual load and ambient conditions history of the transformer for 2017 is used to assess the lifetime utilization of the paper insulation in this period. The moisture content of the test transformer insulation is found to be insignificant, therefore only the temperature and heat dependent aging of the transformer winding insulation is considered. Wind energy generation in 2017 for Anholt is then increased by an upscaling factor in the range of 1.0 to 1.6 pu to identify optimal transformer utilization and to provide insights into transformer dimensioning for offshore windfarms.

2. DEBOTTLENECKING AND OPTIMIZATION OF OWPP EXPORT SYSTEM USING CASE STUDY OF ANHOLT WINDFARM

Offshore Wind Power Plants (OWPP) are often connected to the onshore grid using long HV cables. Depending on the distance from the shore, the OWPP export system based on HVAC technology can consist of two or more substations. The offshore substation, like the one shown for Anholt windfarm in Fig. 1, is located close to the wind turbines and its primary function is to collect the generated wind energy and step-up the voltage for transmission through HV export cables. Whereas, the onshore substation serves as the interface between the export system and the transmission system grid on land. The need for reactor substations depends on the length of the HVAC export cable. These substations house some or all of the following components: HV transformers, shunt reactors, HV filters, dynamic compensators (incl. STATCOM, FACTS, SVC etc.), HV/MV switchgears, LV systems etc.



Figure 1 Offshore substation at Anholt windfarm [10]

High-voltage export cables are known to be the primary bottlenecks in the OWPP export system. Hence, the underutilized potential of the OWPP export system, identified by simplified layout in Fig. 2, can

often be made use of, by switching to Dynamic Thermal Rating (DTR) for the export cables. However, both in the cases of contingency and no contingency, this approach may result in other components with short thermal time constants becoming the bottlenecks. The thermal time constants in oil-filled transformers are relatively short as compared to export cables, which when combined with the capital investment related to transformer dimensioning in the OWPP export system makes these components ideal candidates for DTR.

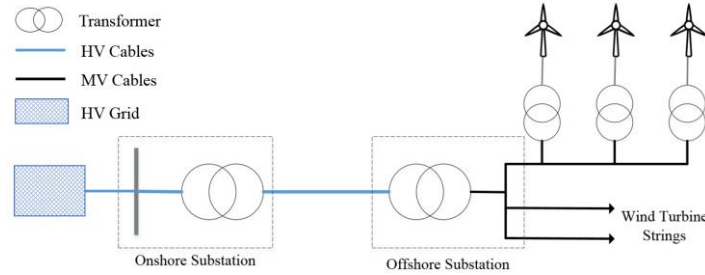


Figure 2. Simplified layout of offshore windfarm's electrical export system

The 400 MW Anholt windfarm in the Kattegat sea, as shown in Fig. 3a, is connected to the transmission system on land with a submarine cable making landfall at the city of Grenå in Jutland (Jylland), Denmark. The 111 wind turbines, each rated 3.6 MW, along with the 33kV array cable system were commissioned by Ørsted, while the export system of the windfarm including the offshore substation was commissioned by the Danish TSO Energinet.dk [10], as shown in Fig. 3b. The 3 export transformers in the offshore substation are rated at 140 MVA each, which brings the total transformer capacity of the export system to 420 MVA. Therefore, during transformer contingency or during planned/unplanned maintenance, dynamic rating of the export transformers seems to be a logical option. For that reason, one of these 140 MVA, 225/33 kV, YNd11, ONAN cooled transformers is used for test cases in this paper.

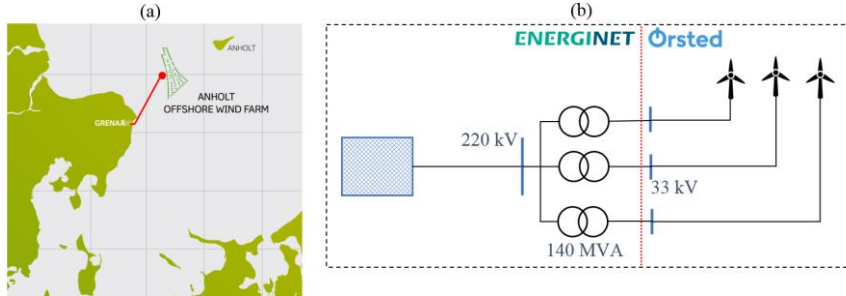


Figure 3 (a) : Location, wind turbine layout and connection for Anholt offshore windfarm [10].
(b) : Export System layout and ownership boundaries for Anholt windfarm

3. THERMOELECTRIC MODELS FOR OIL-FILLED POWER TRANSFORMERS AND VALIDATION FOR ANHOLT WINDFARM TEST CASE

The thermal performance of a power transformer is extremely important to determine because it influences both the operational reliability and the thermal lifetime of the transformer [11] [3]. The Hot-Spot (HST) and Top-Oil (TOT) temperatures can be approximated using differential-equations based thermoelectric models, despite the complex heat transfer phenomena in a transformer [12]. These models are simpler to design as compared to complex Computational Fluid Dynamics and Thermal Hydraulic Network based models [4]. Over the last few decades, a number of thermoelectric models have been proposed to emulate the impacts of varying load and ambient conditions on transformer TOT and HST. These models have been reviewed comprehensively in CIGRE Brochure 659 [13].

The differential-equation based thermoelectric models of international loading guides IEEE C57.91 [5] and IEC 60076-7 [6] are accepted throughout the industry. But these models are found to perform inadequately for low ambient temperature applications during continuously varying load conditions

[14]. In this paper, only the IEEE Clause 7 in C57.91 [5] and Susa *et al.* [7] [8] thermal models are discussed.

3.1 - IEEE Clause 7 Model [5]

According to the IEEE Loading Guide C57.91 (2011), the development of transformer TOT and HST can be determined using the differential equations of (1) and (2).

$$\tau_o \frac{d\vartheta_{tot}}{dt} = \Delta\vartheta_{or} \left(\frac{K(t)^2 R + 1}{R + 1} \right)^n - [\vartheta_{tot}(t) - \vartheta_{amb}(t)] \quad (1)$$

$$\tau_h \frac{d\vartheta_{hst}}{dt} = \Delta\vartheta_{hr} K(t)^{2m} - [\vartheta_{hst}(t) - \vartheta_{tot}(t)] \quad (2)$$

where ϑ_{tot} and ϑ_{hst} represent the calculated Top Oil and Hot Spot Temperatures respectively, expressed in °C. K is the transformer load current in p.u. with rated load current as base; R is the ratio of load losses to no-load losses at rated load; $\Delta\vartheta_{or}$ is the TOT rise over ambient temperature ϑ_{amb} at rated load both expressed in °C, while $\Delta\vartheta_{hr}$ is the rated HST rise over TOT for rated load of 1 pu. The thermal time constants (in hour) for oil τ_o and winding τ_h are usually obtained using the heat run test, but τ_o can also be accurately determined using the approach explained in Section 3.3.

The empirically derived exponents n and m are representative of the transformer cooling mode (ONAN, OFAF etc.). The convective cooling process is varied by the non-linear dependence of heat flow on temperature difference. Therefore, the change in temperature gradients for transformer oil and winding are dependent on the cooling mode which also influences the thermal resistance and oil viscosity [15]. The empirical values of these exponents for different cooling modes, as suggested in [5] are provided in Table I.

3.2 - Susa *et al.* Model [7] [8]

The model proposed by Susa, Lehtonen and Nordman in [7] and further developed in [8] builds upon the fundamental thermoelectric model concepts for transformers proposed by Swift *et al.* in [15] based on the earlier learnings from Nordman [16]. This thermoelectric model introduces the impact of temporal variation of two quantities with respect to temperature: oil viscosity and load losses. The TOT and HST evolution with respect to load and ambient conditions are governed by the following first-order, non-linear, multivariable, differential equations:

$$\tau_o \frac{d\vartheta_{tot}}{dt} = \Delta\vartheta_{or} \left(\frac{K(t)^2 R + 1}{R + 1} \right) - \left(\frac{\vartheta_{tot}(t) - \vartheta_{amb}(t)}{[\mu_{pu}(t) \Delta\vartheta_{hr}]^{1-n'}} \right)^{1/n'} \quad (3)$$

$$\tau_h \frac{d\vartheta_{hst}}{dt} = \Delta\vartheta_{hr} K(t)^2 P_{pu}(\vartheta_{hst}) - \left(\frac{\vartheta_{hst}(t) - \vartheta_{tot}(t)}{[\mu_{pu}(t) \Delta\vartheta_{hr}]^{1-m'}} \right)^{1/m'} \quad (4)$$

The structure of these equations is similar to the IEEE C57.91 models of (1) and (2). All the common symbols represent the same quantities. The oil viscosity μ_{pu} (pu) is the ratio between actual oil viscosity μ_o at time t and oil viscosity at rated TOT rise μ_{or} , as mentioned in (5). This ratio is time variant and temperature dependent, which is a distinctive attribute in the Susa *et al.* model. Similarly, $P_{pu}(\vartheta_{hst})$ presents the dependence of load losses on temperature, which are represented in pu with P_T as base and can be calculated using (6). The dependence of both the copper $P_{cu,pu}$ and eddy losses $P_{e,pu}$ on HST are taken into account in these calculations. The empirical constants in the Susa *et al.* model n' and m' represent the oil circulation mechanism inside the tank and heat dissipation through free or forced convection, and the respective values are tabulated in Table I.

$$\mu_{pu}(t) = \frac{\mu_o(t)}{\mu_{or}} = e^{\left(\frac{2797.3}{\vartheta_{tot}(t) + 273} - \frac{2797.3}{\vartheta_{amb}(t) + \Delta\vartheta_{or} + 273} \right)} \quad (5)$$

$$P_{pu}(\vartheta_{hst}) = P_{cu,pu} \left(\frac{235 + \vartheta_{hst}(t)}{235 + \Delta\vartheta_{hr}} \right) + P_{e,pu} \left(\frac{235 + \Delta\vartheta_{hr}}{235 + \vartheta_{hst}(t)} \right) \quad (6)$$

TABLE I - EMPIRICAL CONSTANTS FOR IEEE [5] AND SUSA [7] MODELS

Transformer Cooling Mode	IEEE C57.91		Susa et al. *	
	n	m	n'	m'
Oil Natural Air Natural (ONAN)	0.8	0.8	0.8	0.67
Oil Natural Air Forced (ONAF)	0.9	0.8	0.83	0.67
Oil Forced Air Forced (OFAF)	0.9	0.8	0.83	0.67
Oil Directed Air Forced (ODAF)	1.0	1.0	0.83	0.67

* values for onload condition (circulating oil) with external cooling are provided

3.3 - Thermal Time Constant for Oil - τ_0

The thermal time constant for oil τ_0 can be calculated using (7)

$$\tau_0 = C_{th} \left(\frac{\Delta\vartheta_{or}}{P_T} \right) \quad (7)$$

$$C_{th} = C_{wdg} M_{wdg} + C_{fe} M_{fe} + C_{mp} M_{mp} + O_{oil} C_{oil} M_{oil} \approx 0.48 M_{oil} \quad (8)$$

Which suggests that τ_0 (hour) is dependent on the rated TOT rise over ambient temperature - $\Delta\vartheta_{or}$, on total transformer losses at rated load P_T (W) and on the thermal capacity of the oil C_{th} (Wh/°C). The thermal capacity of oil can either be approximated using the method suggested in [5], which requires detailed transformer information or by using the simplified empirical formulation of [7] that requires only the mass of the oil. Both these formulations are provided in (8). Where, M_{wdg} , M_{fe} , M_{mp} and M_{oil} represent the weights of windings, iron core, tank (metal parts) and oil respectively in kilograms. The remaining terms are explained and the relevant values are provided in Table II.

TABLE II - CONSTANTS FOR DETERMINING THERMAL TIME CONSTANT FOR OIL [5]

Symbol	Description	Value	Unit
C_{wdg}	Specific Heat Capacity of Winding (Copper)	0.11	Wh/kg °C
	Specific Heat Capacity of Winding (Aluminum)	0.25	Wh/kg °C
C_{fe}	Specific Heat Capacity of Iron Core	0.13	Wh/kg °C
C_{mp}	Specific Heat Capacity of Tank and Metal Parts	0.13	Wh/kg °C
C_{oil}	Specific Heat Capacity of Oil	0.51	Wh/kg °C
O_{oil}	Correction factor for oil (ONAF, ONAN, OFAF)	0.86	-
	Correction factor for oil (ODAF)	1.0	-

* Correction factors are based on the modeling performed in [8] and [16]

3.4 - Comparison of models

The viscosity of transformer oil varies with temperature. This variation is extreme for temperatures lower than 10 °C and even though it is rather trivial for oil temperatures in the range of 40 to 100 °C, its variation is still most dominant in this temperature range when compared with the remaining physical properties of the oil including density, specific heat, thermal conductivity and expansion coefficients etc. [17]. Since the convective cooling capacity is directly dependent on viscosity, Susa rightly takes this into account for both the HST and TOT estimation, which is ignored by the IEEE C57.91 models. Similarly, the temperature dependence of load losses in the Susa *et al.* model increases the degree of accuracy to some extent. The thermoelectric models provided by IEEE in (1) and (2) and by Susa *et al.* in (3) and (4) are based on the following similar structure:

$$Temperature\ Change = f(Heat\ in) - f(Heat\ out)$$

The time varying load drives the Heat-In expression of the equation while the difference in relevant temperatures defines the Heat-Out process. Despite the similarity in structure, the convective cooling process is very different for the two models, which is due to the location of empirical constants. The empirically derived exponents n and m are placed with the load losses (Heat-In) in the IEEE model, while Susa *et al.* model puts these on the heat-out expression which is thermodynamically more accurate. It is observed that both the models obtain similar forms if the constants are set to 1 but differ significantly otherwise. Both these models depend heavily upon the transformer parameters that are obtained through heat-run tests. Therefore, the performance of both the models would be poor if appropriate protocols are not followed during the temperature-rise test or if any of the required parameters are not known.

Despite the limitations in accuracy of the IEEE Clause 7 model, it is widely used because of its simplified formulation. The model can be linearized easily allowing implementation of optimization algorithms for wide-scale dynamic rating application, a task that would be challenging with Susa *et al.* model.

3.5 – Validation Results for Anholt Export Transformer

The validation of Top Oil Temperature calculated using the IEEE C57.91 model of (1) and (2) and Susa *et al.* model of (3) and (4) is performed with the measured TOT for the 140 MVA export transformer for Anholt windfarm. The calculated TOT is based on the test transformer's recorded load and ambient temperature. Hot Spot temperatures are not used as the parameters for performance evaluation of these models because of unavailability of HST measurements for the test transformers. The validation results including transformer load, TOT, HST and ambient temperature are provided in Fig. 4 for the months of January and July in 2017 to emulate considerably different ambient conditions. It can be seen that the measured TOT is usually extremely close to the TOT calculated using Susa *et al.* model for both the test periods, with the green line often overlapping the red line. This accuracy is even more evident for low ambient temperatures of January as compared to the temperatures predicted by IEEE model, which is because of the correct approximation of oil viscosity variation with ambient temperature in the Susa model. During low load periods, the TOT calculated using Susa model remains slightly higher than the measured TOT. Therefore, transformer damage can be prevented due to conservative estimation during possible dynamic loading operation. The TOT calculated using IEEE model, on the other hand, almost always results in underestimation. The error between calculated and measured TOT accumulated over the entire 2017 is 53.3% higher for the IEEE model as compared to the Susa *et al.* model, therefore the rest of the analysis related to HST in this paper is performed using the Susa *et al.* model.

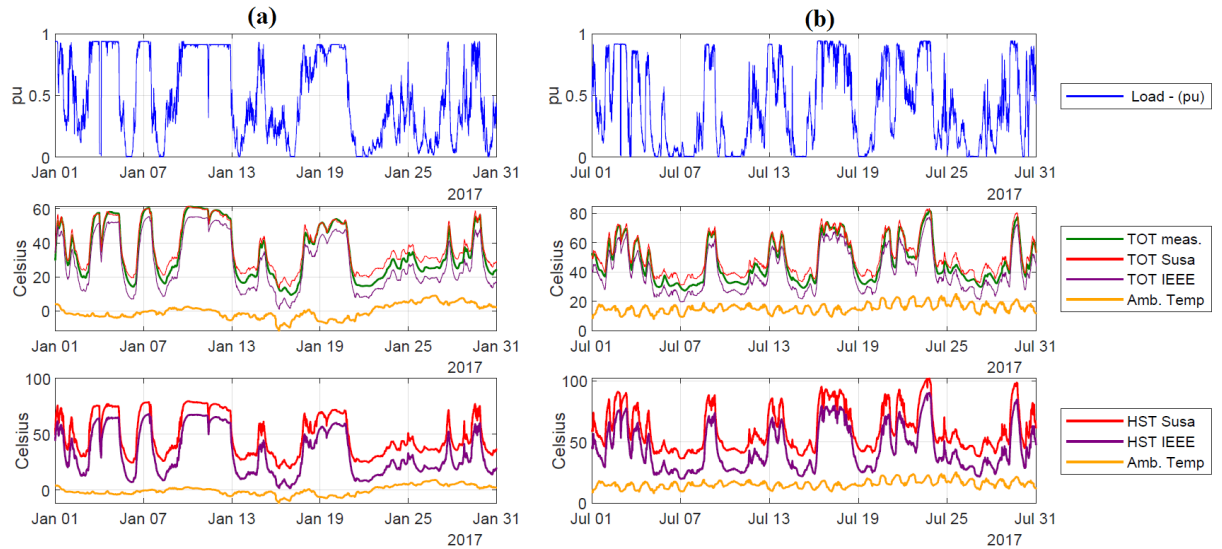


Figure 4. (a): Validation results for January–2017. (b): Validation results for July-2017
Top: Transformer load variation; Middle: Temperatures including Ambient, measured TOT and calculated TOT;
Bottom: Temperatures including Ambient, Calculated HST (IEEE and Susa)

4. THERMAL AGING AND LIMITS FOR ANHOLT EXPORT TRANSFORMERS

Unlike power transformers in the transmission system, windfarm export system transformers are responsible for the transmission of generated wind energy only. Therefore, the intermittent nature of the wind plays a huge role in the utilization of the test transformer. Hence, in order to assess the impact of wind generation patterns on thermal aging of transformer paper insulation in one year, the actual loading and ambient condition history of the 140 MVA windfarm transformers for the year 2017 with 1-minute sampling rate are used.

The degradation mechanism of cellulose, which is the principal component of transformer winding insulation, depends principally on three agents: water, oxygen and heat [5]. But since heat is dependent on transformer loading, while the transformer oil preservation system is responsible for both the insulation water and oxygen content, only the heat-dependent aging of the paper insulation is studied in this paper. This is further complemented by the fact that the studied transformer had been in operation for a relatively small time (<5 years), which is the case for most offshore windfarm transformers with maximum 25 years operation limit. This results in comparatively high insulation tensile strength retention by the end of transformer operation life. Moreover, the oxygen and water content are found to be insignificant for the test transformer.

Dynamic loading of a transformer beyond its rated capacity results in thermal stress which is maximum at the HST location, typically close to the paper insulation at the top winding region. For the reasons explained above, instead of using the Degree of Polymerization (DP), the accelerated aging of paper due to HST thermal stress is directly evaluated to assess the transformer insulation's loss-of-life (*LOL*) using (9) for thermally upgraded paper which is based on Arrhenius reaction rate theory [5] [6].

$$LOL(t) = \int_{t_0}^t e^{\left(\frac{15000}{110+273} - \frac{15000}{\vartheta_{hst}(\tau)+273}\right)} d\tau \quad (9)$$

The cumulative loss-of-life (*LOL*) for the period between t_0 and t represents the aging of paper insulation only, which is the predominant aging phenomenon for transformers that have been in the field for less than 20 years [18]. Other phenomena including residual moisture content in oil/paper, degradation products etc. and the respective aging impacts are not addressed for the test transformer.

The TOT and HST limits specified in international loading guides IEEE C57.91 [5] and IEC 60076-6 [6] for large power transformers are summarized in Table III for different dynamic loading periods. The maximum continuous HST limit of 110 °C recommended by transformer manufacturers for thermally upgraded paper is hardly ever reached because of protection designs, favorable ambient conditions and conservative operation philosophies. The analysis in this paper limits the HST to 140 °C, as the dielectric strength of the transformer insulation is at severe risk at temperatures greater than 140 °C because of acceleration in chemical reactions in oil and formation of gas bubbles [6]. It must be noted that this limit can reduce significantly with increase in the moisture content, but for reasons explained above these impacts are not investigated further in this paper.

TABLE III - THERMAL LIMITS FOR LARGE POWER TRANSFORMERS [5] [6]

	Normal Cyclic Loading	Emergency Loading (long-term)	Emergency Loading (<30 min)
HST	120 °C	140 °C	160/180 °C
TOT	105 °C	115 °C	115/110 °C

Referring to Fig. 5, the test transformer at Anholt windfarm is found to be statically loaded below its rated capacity throughout 2017 resulting in maximum HST of less than 100 °C. Consequently, the thermal loss-of-life of the test transformer's paper insulation is approximately 25 days in 2017 which is considerably less than the design *LOL* of 365 days, as shown in Fig. 6.

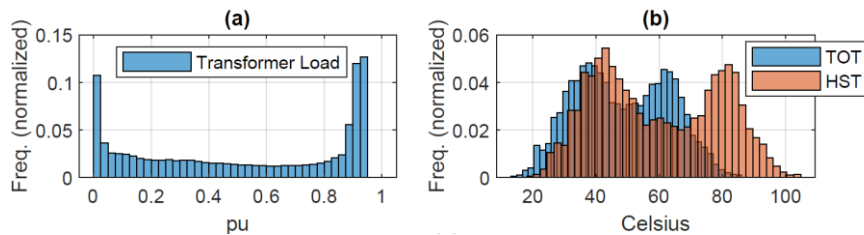


Figure 5 Anholt windfarm transformer utilization in 2017. Histograms for transformer pu load (a) and temperatures (b)

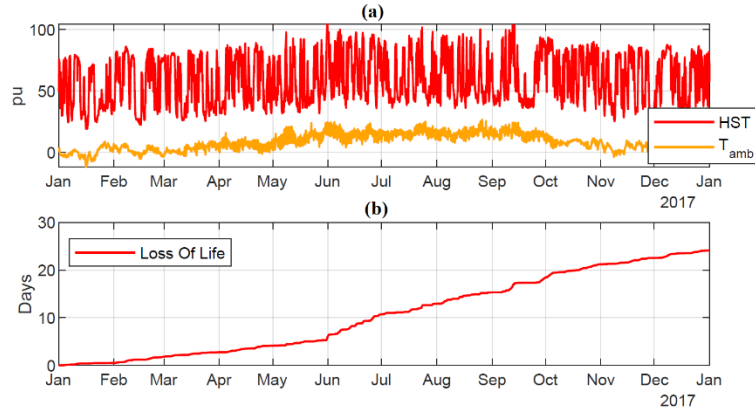


Figure 6. Anholt windfarm transformer utilization in 2017. (a) Ambient Temp. and Calculated HST. (b) Thermal loss-of-life of paper insulation

5. INCREASE IN WIND ENERGY GENERATION FOR OPTIMAL TRANSFORMER UTILIZATION

The discussion so far has established that, thermally, the unutilized potential of windfarm transformers is significant. Therefore, the test case assesses the thermal development of the Anholt windfarm export transformer for increased wind energy generation and evaluates the thermal loss-of-life (LOL) for transformer paper insulation in 1 year using the methodology explained in the previous section. The wind energy generation is increased by upscaling the actual instantaneous load of the test transformer for the entire period of 2017. The upscaling factor ' W ' is varied over the range of 1.0 to 1.6 pu with actual instantaneous wind generation in 2017 at Anholt as base. Consequently, two different situations with similar repercussions are emulated. Firstly, in case of long-term transformer contingency (i.e. losing one of the three transformers for a period of 1 year), it is important to assess whether the remaining two transformers can take up the additional 0.5 pu load for short term without resulting in permanent damage to the transformer insulation due to accelerated thermal aging. This is however assessed with the assumptions that the remaining export system components (incl. bus couplers, bus bars, instrument transformers etc.) are dimensioned for n-1 contingency case to bear this additional load and the water and oxygen contamination of the insulation is controlled. Secondly, the assessment of thermal lifetime utilization of the test windfarm transformer for this additional load resembles the situation of offshore windfarm expansion, which can provide insights into transformer dimensioning for OWPP applications.

These impacts are assessed by calculating two critical parameters for the test transformers. The first parameter is the cumulative loss-of-life (LOL) for transformer paper insulation at the end of the year, based on (9). Secondly, the probability of violating the Normal Cyclic and long-term Emergency loading limits of Table III for HST is evaluated by calculating the probability of two possibilities: how frequently the HST limit of 140 °C is crossed and for how long the limits are continuously sustained (i.e. whether the time limits for cyclic and long-term emergency HST limits are violated). The short-term emergency limits are not considered in this paper because of adverse effects of $HST > 140$ °C. The calculated probability is represented by the expression ' $1 - prob(HST_{max})$ ', whose values ranges between 0 and 1, where 1 suggests that the limits are never violated throughout the year and 0 represents the contrary.

The transformer loads and calculated HST for the test transformer are provided in Fig. 7 for different upscaling factors for 3 days in Summer 2017. Referring to Fig. 8(a), it is shown that for the given assumptions, the transformer paper insulation lifetime is optimally utilized without violating the thermal limits of Table III for the upscaling factor W of up to 1.52 pu. The thermal aging of paper insulation increases drastically beyond this point because HST starts violating the thermal limits (including bubbling temperature) more frequently and for longer periods resulting in ' $1 - prob(HST_{max})$ ' value of less than 1. This is also visible in Fig. 8(b) where HST never crosses the 140 °C limit for $W = 1.5$ pu. The thermal loss-of-life for the test transformer's insulation is extremely close to designed LOL of 365 days in 2017 for W between 1.5 and 1.52 pu, as shown in Fig. 8(c). Therefore, it is demonstrated that the test transformer could have taken up the additional 0.5 pu load throughout 2017 in case of

contingency of one of the export transformers. Based on this discussion it can be deduced that, thermally, the export transformers for Anholt windfarm can fulfill the $n-1$ contingency requirements for long periods and can comfortably allow further wind energy integration in the existing export system.

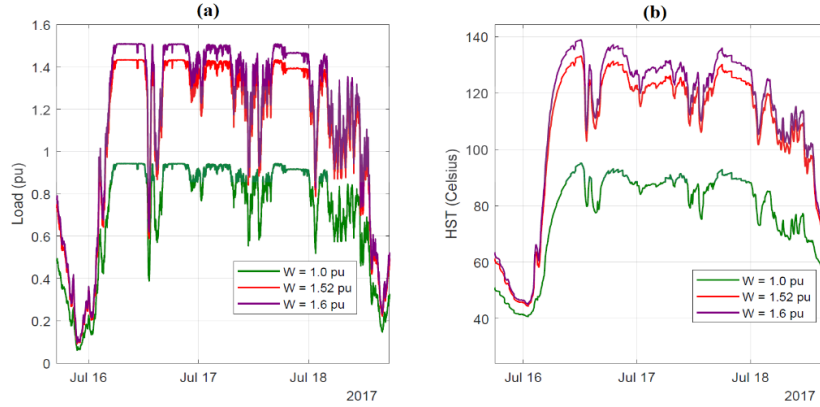


Figure 7. (a) Transformer load (b) Calculated HST for different upscaling factors 'W' for 3 days in Summer 2017

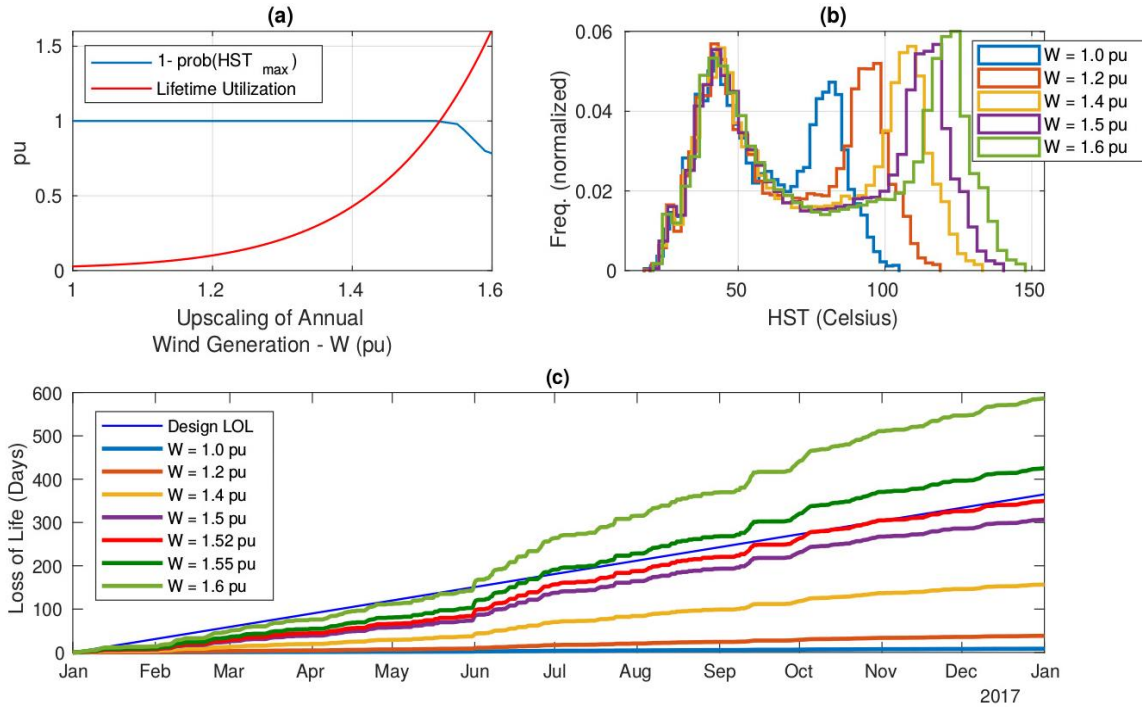


Figure 8. (a): Impact of Wind Generation Increase on Test Transformer. (b): Test Transformer's Year-Round HST Distribution for Increased Wind Generation. (c): Thermal Lifetime Utilization of Test Transformer for Increased Wind Generation. 'W' represents the upscaling factor of wind generation in pu with actual generation in 2017 as base.

6. CONCLUSIONS

The investigation has shown that the intermittent nature of the wind plays a considerable role in thermal utilization of offshore windfarm export transformers, which results in a significant unutilized potential. The thermal utilization is addressed using the loss-of-life of paper insulation due to hot-spot temperature only. This mechanism is known to be the dominant aging phenomena during early-years of transformer operation with functional oil preservation system. The analysis concludes that the intermittent nature of the wind has to be taken into account for transformer design and dimensioning for offshore windfarm applications. It is also shown using the case study of the Danish Anholt offshore windfarm that transformers can potentially be offshore transmission bottlenecks during contingency, but these bottlenecks can be resolved by prolonged dynamic rating operation beyond the transformer's nameplate rating. This characteristic can also facilitate further wind energy integration in the existing export system for offshore windfarms.

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